

Gamma-Ray Bursts*

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Ultra-high-energy, $> 10^{19}$ eV, cosmic-ray and high energy, $\sim 10^{14}$ eV, neutrino production in GRBs is discussed in the light of recent GRB and cosmic-ray observations. Emphasis is put on model predictions that can be tested with operating and planned cosmic-ray and neutrino detectors, and on the prospects of testing for neutrino properties.

1. Introduction

The origin of GRBs, bursts of 0.1 MeV—1 MeV photons lasting for a few seconds, remained unknown for over 20 years, primarily because GRBs were not detected prior to 1997 at wave-bands other than γ -rays [1]. The isotropic distribution of bursts over the sky suggested that GRB sources lie at cosmological distances, and general phenomenological considerations were used to argue that the bursts are produced by the dissipation of the kinetic energy of a relativistic expanding fireball (see [2] for review).

Adopting the cosmological fireball hypothesis, it was shown that the physical conditions in the fireball dissipation region allow Fermi acceleration of protons to energy $> 10^{20}$ eV [3,4], and that the average rate at which energy is emitted as γ -rays by GRBs is comparable to the energy generation rate of UHECRs in a model where UHECRs are produced by a cosmological distribution of sources [3]. Based on these two facts, it was suggested that GRBs and UHECRs have a common origin (see [5] for a recent review).

In the last two years, afterglows of GRBs have been discovered in X-ray, optical, and radio wave bands [6]. Afterglow observations confirmed the cosmological origin of the bursts, through the redshift determination of several GRB host-galaxies, and confirmed standard model predictions of afterglows that result from the collision of an expanding fireball with its surrounding medium [2]. These observations therefore provide strong support for the GRB model of UHECR production.

In this review, UHECR and neutrino production in GRBs is discussed in the light of recent GRB and UHECR observations. The fireball model is briefly described in §2.1, and proton acceleration in GRB fireballs is discussed in §2.2. Implications of recent afterglow

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observations to high energy particle production are discussed in §3. Model predictions are shown to be consistent with the observed UHECR spectrum in §4. Predictions of the GRB model for UHECR production, that can be tested with future UHECR experiments, are discussed in §5. High energy neutrino production in fireballs and its implications for future high energy neutrino detectors are discussed in §6.

2. UHECR from GRB fireballs

2.1. The fireball model

In the fireball model of GRBs, a compact source, of linear scale $r_0 \sim 10^7$ cm, produces a wind characterized by an average luminosity $L \sim 10^{52} \text{ erg s}^{-1}$ and mass loss rate $\dot{M} = L/\eta c^2$. At small radius, the wind bulk Lorentz factor, Γ , grows linearly with radius, until most of the wind energy is converted to kinetic energy and Γ saturates at $\Gamma \sim \eta \sim 300$. Variability of the source on time scale $\Delta t \approx r_0/c \sim 1$ ms, resulting in fluctuations in the wind bulk Lorentz factor Γ on similar time scale, lead to internal shocks in the expanding fireball at a radius $r_i \approx \Gamma^2 c \Delta t$. These shocks reconvert part of the kinetic energy to internal energy, which is then radiated as γ -rays by synchrotron emission of shock-accelerated electrons. The γ -ray flux is observed to vary on time scale $t_{\text{var}} \sim r_i/\Gamma^2 c \sim \Delta t$.

As the fireball expands, it drives a relativistic shock (blast wave) into the surrounding gas. At a radius $r \sim \Gamma^2 c T$, where $T \sim 10$ s is the wind duration, most of the fireball energy is transferred to the surrounding gas, and the flow approaches self-similar expansion. The shock driven into the ambient medium at this stage continuously heats new gas, and accelerates relativistic electrons that produce by synchrotron emission the delayed radiation, “afterglow,” observed on time scales of days to months. As the shock-wave decelerates, the emission shifts with time to lower frequency.

2.2. Fermi acceleration in GRBs

The observed GRB and afterglow radiation is produced by synchrotron emission of shock accelerated electrons. In the region where electrons are accelerated, protons are also expected to be shock accelerated. This is similar to what is thought to occur in supernovae remnant shocks [7]. Internal shocks are generally expected to be “mildly” relativistic in the fireball rest frame, i.e. characterized by Lorentz factor $\gamma_i - 1 \sim 1$, since adjacent shells within the wind are expected to expand with Lorentz factors which do not differ by more than an order of magnitude. We therefore expect results related to particle acceleration in sub-relativistic shocks [7] to be valid for the present scenario. In particular, the predicted energy distribution of accelerated protons is $dN_p/dE_p \propto E_p^{-2}$.

Two constraints must be satisfied by fireball wind parameters in order to allow proton acceleration to $E_p > 10^{20}$ eV in internal shocks [3]:

$$\xi_B/\xi_e > 0.02 \Gamma_{300}^2 E_{p,20}^2 L_{\gamma,52}^{-1}, \quad (1)$$

in order for the proton acceleration time t_a to be smaller than the wind expansion time, and

$$\Gamma > 130 E_{20}^{3/4} \Delta t_{10\text{ms}}^{-1/4}, \quad (2)$$

in order for the synchrotron energy loss time of the proton to be larger than t_a . Here, $\Gamma = 300\Gamma_{300}$, $\Delta t = 10\Delta t_{10\text{ms}}$ ms, $E_p = 10^{20}E_{p,20}$ eV, $L_\gamma = 10^{52}L_{\gamma,52}$ erg/s is the γ -ray luminosity, ξ_B is the fraction of the wind energy density which is carried by magnetic field, $4\pi r^2 c \Gamma^2 (B^2/8\pi) = \xi_B L$, and ξ_e is the fraction of wind energy carried by shock accelerated electrons.

Eqs. (1) and (2) imply that protons may be accelerated in a GRB wind to energy $> 10^{20}$ eV, provided that $\Gamma > 100$ and that the magnetic field is close to equipartition with electrons. The former condition, $\Gamma > 100$, is remarkably similar to that inferred based on γ -ray spectra. There is no theory at present that allows a basic principles calculation of the strength of the magnetic field. However, magnetic field close to equipartition, $\xi_B \sim 1$, is required in order to account for the observed γ -ray emission.

We have assumed in the discussion so far that the fireball is spherically symmetric. However, since a jet-like fireball behaves as if it were a conical section of a spherical fireball as long as the jet opening angle is larger than Γ^{-1} , our results apply also for a jet-like fireball (we are interested only in processes that occur when the wind is ultra-relativistic, $\Gamma \sim 300$, prior to significant fireball deceleration). For a jet-like wind, L in our equations should be understood as the luminosity the fireball would have carried had it been spherically symmetric.

3. Implications of afterglow observations

In addition to providing support to the validity of the qualitative fireball scenario described in §2.1, afterglow observations provide quantitative constraints on fireball model parameters. The determination of GRB redshifts implies that the characteristic GRB γ -ray luminosity and emitted energy are $L_\gamma \sim 10^{52}$ erg/s and $E_\gamma \sim 10^{53}$ erg respectively, an order of magnitude higher than the values assumed prior to afterglow detection. Afterglow observations also indicate that $\xi_e \sim \xi_B \sim 0.1$. This suggests that the constraint (1) is indeed satisfied, allowing proton acceleration to $> 10^{20}$ eV.

The observed GRB redshift distribution implies a GRB rate of $R_{\text{GRB}} \sim 10/\text{Gpc}^3\text{yr}$ at $z \sim 1$. The present, $z = 0$, rate is less well constrained, since most observed GRBs originate at redshifts $1 \leq z \leq 2.5$ [8]. Present data are consistent [8] with both no evolution of GRB rate with redshift, and with strong evolution (following, e.g., the luminosity density evolution of QSOs or the evolution of star formation rate), in which $R_{\text{GRB}}(z = 1)/R_{\text{GRB}}(z = 0) \sim 8$. The energy observed in γ -rays reflect the fireball energy in accelerated electrons. If shock accelerated protons and electrons carry similar energy, as indicated by afterglow observations, then the $z = 0$ rate of cosmic-ray production by GRBs is similar to the generation rate of γ -ray energy,

$$E^2(d\dot{n}_{CR}/dE)_{z=0} \approx 10^{44}\zeta\text{erg/Mpc}^3\text{yr}, \quad (3)$$

where ζ is in the range of ~ 1 to ~ 8 .

4. Comparison with UHECR observations

In Fig. 1 we compare the UHECR spectrum, reported by the Fly's Eye [9], the Yakutsk [10], and the AGASA [11] experiments, with that predicted by the GRB model. The flattening of the cosmic-ray spectrum at $\sim 10^{19}$ eV, combined with the lack of anisotropy

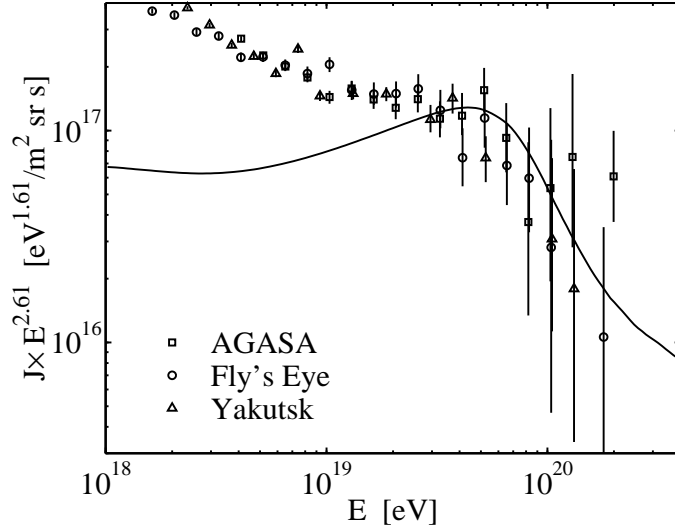


Figure 1. The UHECR flux expected in a cosmological model, where high-energy protons are produced at a rate $(E^2 d\dot{n}_{CR}/dE)_{z=0} = 0.8 \times 10^{44} \text{ erg/Mpc}^3 \text{ yr}$ as predicted in the GRB model [Eq. (3)] (The flux above 10^{19} eV is not sensitive to the z dependence of $E^2 d\dot{n}_{CR}/dE$). 1σ flux error bars are shown. The highest energy points are derived assuming the detected events (1 for Fly's Eye and Yakutsk, 4 for AGASA) represent a uniform flux over the energy range 10^{20} eV– 3×10^{20} eV.

and the evidence for a change in composition from heavy nuclei at low energy to light nuclei (protons) at high energy [12], suggest that an extra-Galactic source of protons dominates the flux at $E > 10^{19}$ eV. The UHECR flux predicted by the GRB model is in remarkable agreement with the observed extra-Galactic flux.

The suppression of model flux above $10^{19.7}$ eV is due to energy loss of high energy protons in interaction with the microwave background, i.e. to the “GZK cutoff” [13]. Both Fly's Eye and Yakutsk data show a deficit in the number of events, consistent with the predicted suppression. The deficit is, however, only at a 2σ confidence level [5]. The AGASA data is consistent with Fly's Eye and Yakutsk results below 10^{20} eV. A discrepancy may be emerging at higher energy, $> 10^{20}$ eV, where the Fly's Eye and Yakutsk experiments detect 1 event each, and the AGASA experiment detects 6 events for similar exposure.

The flux above 10^{20} eV is dominated by sources at distances < 40 Mpc. Since the distribution of known astrophysical systems (e.g. galaxies, clusters of galaxies) is inhomogeneous on scales of tens of Mpc, significant deviations from model predictions presented in Fig. 1 for a uniform source distribution are expected above 10^{20} eV. Clustering of cosmic-ray sources leads [14] to a standard deviation, σ , in the expected number, N , of events above 10^{20} eV, given by $\sigma/N = 0.9(d_0/10\text{Mpc})^{0.9}$, where d_0 is the unknown scale length of the source correlation function and $d_0 \sim 10$ Mpc for field galaxies.

An order of magnitude increase in the exposure of UHECR experiments, compared to that available at present, is required to test for the existence of the GZK cutoff. Such

exposure would allow this test through an accurate determination of the spectrum in the energy range of $10^{19.7}$ eV to 10^{20} eV, where the effects of source inhomogeneities are expected to be small [14]. Moreover, an order of magnitude increase in exposure will also allow to determine the source correlation length d_0 , through the detection of anisotropies in the arrival directions of $\sim 10^{19.5}$ eV cosmic-rays over angular scales of $\Theta \sim d_0/30$ Mpc [14].

5. GRB model predictions for planned UHECR experiments

The rate at which GRBs occur within a distance of ~ 100 Mpc from Earth, the distance to which $> 10^{20}$ eV proton propagation is limited due to interaction with the microwave background, is ~ 1 per 100 yr. This rate can be reconciled with the detection of several $> 10^{20}$ eV events over a period of a few years only if there is a large dispersion, ≥ 100 yr, in the arrival time of protons produced in a single burst. The required dispersion is likely to result from deflection by random magnetic fields [3]. A proton of energy E propagating over a distance D through a magnetic field of strength B and correlation length λ is deflected by an angle $\theta_s \sim (D/\lambda)^{1/2} \lambda/R_L$, which results in a time delay, compared to propagation along a straight line, $\tau(E, D) \approx \theta_s^2 D/4c \propto B^2 \lambda$. The random energy loss suffered by $> 10^{20}$ eV protons as they propagate, owing to the production of pions, implies that protons observed at Earth with given energy have different energy histories along their propagation path. Thus, magnetic field deflection results not only in a delay, but also in a spread in arrival time of protons of fixed energy, comparable to the delay τ .

The current upper bound on the inter-galactic magnetic field [15], $B\lambda^{1/2} \leq 10^{-9}$ G Mpc $^{1/2}$, allows a spread $\tau(E = 10^{20}\text{eV}, D = 100\text{Mpc}) \sim 10^5$ yr, well above the minimum, $\tau \sim 100$ yr, required in the model. The magnetic field upper bound implies an upper bound on the number of GRBs contributing to the $> 10^{20}$ eV flux at any given time, $\sim 10^5/100 = 10^3$. The upper bound on the number of sources contributing to the flux above E decreases rapidly as E increases beyond 10^{20} eV, as the propagation distance decreases with energy due to the increase in pion production energy loss rate. This rapid decrease implies that at $E \sim 3^{20}$ eV there can be only a few sources contributing to the flux at any given time [16].

The GRB model therefore makes a unique prediction [16]: The UHECR flux at energy $E \geq 3 \times 10^{20}$ eV should be dominated by a few sources on the sky. These sources should have narrowly peaked energy spectra, and the brightest sources should be different at different energies. This is due to the fact that at any fixed time a given burst is observed in UHECRs only over a narrow range of energy: If a burst is currently observed at some energy E then UHECRs of much lower (higher) energy from this burst will arrive (have arrived) mainly in the future (past). Testing the GRB model predictions requires an exposure 10 times larger than that of present experiments. Such increase is expected to be provided by the planned Auger [17] detectors.

6. 10^{14} eV Neutrinos

Protons accelerated in the fireball to high energy lose energy through photo-pion production in interaction with fireball photons. The decay of charged pions results in the production of high energy neutrinos [18]. The observed energy of a proton, for which the

observed 1 MeV photons are at the threshold of the Δ -resonance, is $0.2 \text{ GeV}^2 \Gamma^2 / 1 \text{ MeV}$. Typically, the neutrino receives $\sim 5\%$ of the proton energy. Thus, the typical energy of neutrinos resulting from interaction of accelerated protons with GRB photons is

$$E_\nu^b \approx 5 \times 10^{14} \Gamma_{300}^2 \text{ eV}. \quad (4)$$

The flux normalization is determined by the efficiency of pion production. The fraction of energy lost to pion production by protons producing the neutrino flux above E_ν^b is essentially independent of energy and is given by [18]

$$f_\pi \approx 0.2 \frac{L_{\gamma,52}}{\Gamma_{300}^4 \Delta t_{10\text{ms}}}. \quad (5)$$

If GRBs are the sources of UHECRs, then using Eq. (5) and Eq. (3) with $\zeta \simeq 1$, the expected GRB neutrino flux is [18]

$$E_\nu^2 \Phi_{\nu_x} \approx 1.5 \times 10^{-9} \left(\frac{f_\pi}{0.2} \right) \times \min\{1, E_\nu/E_\nu^b\} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}, \quad (6)$$

where ν_x stands for ν_μ , $\bar{\nu}_\mu$ and ν_e .

The flux of $\sim 10^{14} \text{ eV}$ neutrinos given in Eq. (6) implies that large area, $\sim 1 \text{ km}^2$, high-energy neutrino telescopes, which are being constructed to detect cosmologically distant neutrino sources [19], would observe several tens of events per year correlated in time and in arrival direction with GRBs. Detection of neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of $\sim 1 \text{ s}$ ($\sim 1 \text{ ms}$ for short bursts), checking the assumption of special relativity that photons and neutrinos have the same limiting speed to one part in 10^{16} , and the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential, to one part in 10^6 (considering the Galactic potential alone).

The model discussed above predicts the production of high energy muon and electron neutrinos. However, if the atmospheric neutrino anomaly has the explanation it is usually given, oscillation to ν_τ 's with mass $\sim 0.1 \text{ eV}$ [20], then one should detect equal numbers of ν_μ 's and ν_τ 's. Up-going τ 's, rather than μ 's, would be a distinctive signature of such oscillations. Since ν_τ 's are not expected to be produced in the fireball, looking for τ 's would be an ‘‘appearance experiment.’’ To allow flavor change, the difference in squared neutrino masses, Δm^2 , should exceed a minimum value proportional to the ratio of source distance and neutrino energy. A burst at 100 Mpc producing 10^{14} eV neutrinos can test for $\Delta m^2 \geq 10^{-16} \text{ eV}^2$, 5 orders of magnitude more sensitive than solar neutrinos.

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